MODAL PARAMETER ESTIMATION FOR OPERATIONAL WIND TURBINES

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ABSTRACT

Wind turbines are time-varying systems excited by loads due to the wind and to the interaction between blades, tower and drivetrain. Since it is very difficult to measure the loads, the modal identification procedure needs to rely only on the output measurement data. Operational Modal Analysis (OMA) is well suited for the estimation of modal parameters in several cases. One of the main conditions needed for its application is the linear time-invariance of the system. It is the case of parked wind turbines, but the requirement is violated in the case of operating wind turbines. Therefore, OMA technique needs to be adapted in order to be applied to linear time-variant systems. Alternatively, time-variant systems should be converted to time-invariant ones before applying the classical OMA.

Multi-Blade Coordinate transformation (MBC) allows having information on the dynamic interaction between the nonrotating components and the rotor. The time periodic system is converted into a time invariant one. Conventional OMA technique can then be applied to estimate the modal parameters. First of all a multibody model of a wind turbine is considered and some assessments on how to combine numerical and experimental techniques for Structural Health Monitoring (SHM) of operating wind turbines are investigated.

KEYWORDS : *Wind turbines; Operational Modal Analysis; Multi-Blade (Coleman) transformation; Dynamic characterization.*

INTRODUCTION

Most existing techniques for estimating the modal parameters of a system (natural frequencies, damping and mode shapes) are based on the assumption that the system itself can be considered as linear time-invariant (LTI). A wind turbine in operating conditions cannot be modeled as a LTI system, which limits the applicability of conventional modal analysis methods. If the angular speed of the rotor is constant with a good approximation, then the wind turbine can be treated as Linear Time Periodic (LTP) and its dynamic behavior can be characterized by means of different methods than the ones used for LTI systems.

Floquet theory [1], regarding linear differential equations with periodic coefficients, has been developed in the late 1800s and it has been widely applied to several structures such as helicopters and wind turbines. Coleman theory [2] has also been used for helicopter analysis. It consists of a transformation used to convert the rotating degrees of freedom into a non-rotating frame. By means of the transformation, also known as Multi-Blade Coordinate (MBC) transformation, the ground resonance problem was identified. It has also been used for studying the stability and the aeroelastic behavior of three-bladed wind turbines [3].

A Floquet analysis has many drawbacks including ambiguity of the natural frequencies and difficulty in identifying modes, while MBC provides more physical insights to identify the modal properties. A comparison between the two methods [4] shows that the difference is not very large and it does not lead to different stability conclusions. The best solution is that the first step is the use of MBC examining the periodic variation of the system. If variations are small, then a Floquet analysis would not be useful. If periodic variations are large, then a Floquet analysis should follow MBC to take advantage of the improved system conditioning.

The main assumption needed for the application of MBC transformation is related to the isotropy of the system, which means that the three blades have to be identical both from an aerodynamic and a structural point of view. This property can be used for identifying asymmetries of the system for structural health monitoring purposes. In fact, after the transformation, the nominal case will have zero-mean residuals, while the faulty case will have non-zero mean residuals.

In the following sections, the theoretical background of MBC transformation and Operational Modal Analysis (OMA) are given and, then, the aeroelastic model of the NREL 5-MW wind turbine will be presented and the techniques will be applied in order to identify the modal parameters in operating conditions.

1 THEORETICAL BACKGROUND

1.1 Multi-Blade Coordinate transformation

In general, the dynamic behavior of wind turbine blades is expressed in rotating frames attached to the individual blades. It does not take into account the fact that the rotor responds as a single system to excitation such as wind gusts, control inputs and relative motion between the tower and the nacelle. Multi-Blade Coordinate transformation (MBC) allows integrating the dynamics of individual blades in a non-rotating frame. After that, the rotor can be combined with the other subsystems in order to analyse the coupled behavior of the wind turbine.

This procedure offers several advantages. First of all, the dynamic interaction between the rotor and the fixed subsystems can be modeled. A better understanding into rotor dynamics is possible and most of the periodic terms are filtered out, except the ones which are integral multiples of ΩN, where Ω is the rotor angular speed and N is the number of rotor blades. In order to filter out all the harmonics, the MBC tool need to be combined with a harmonic removal tool.

From a mathematical point of view, consider a horizontal axis wind turbine (HAWT) with three blades spaced equally around the rotor azimuth. In this case, the azimuth location of *b*-th blade is given by Equation (1):

$$\psi_b = \psi_1 + (b-1)\frac{2\pi}{3} \quad ; \text{b=1, 2, 3} \tag{1}$$

It is implicitly assumed that the three blades are uniformly distributed, which means one blade each 120° in the rotor plane. ψ_b is the instantaneous azimuth angle of the *b*-th blade, while ψ_1 is the azimuth angle of the first (reference) blade and it is equal to 0 when the blade is vertically up. The set of three coordinates $\{q_{1,i}, q_{2,i}, q_{3,i}\}^T$, measured at the location i on the blades 1, 2, 3, is converted by means of MBC transformation to the three multi-blade coordinates, expressed in the Equations (2) as: $\{q_{0,i}, q_{c,i}, q_{s,i}\}^T$.

The new coordinates can also be called rotor coordinates since they express the cumulative behavior of all the rotor blades in the non-rotating frame. Their physical interpretation is not immediate and it depends on the degree of freedom they refer to. For example, if q_b is a flap degree of freedom, then q_0 is the rotor coning, $q_{c,1}$ is the rotor tip-path-plane fore-aft tilt about a horizontal axis normal to the rotor shaft, and $q_{s,1}$ is the rotor tip-path-plane side-side tilt about a vertical axis normal to the rotor shaft.

$$q_{0,i} = \frac{1}{N}\sum_{b=1}^{N} q_{b,i} \; ; \qquad q_{c,i} = \frac{2}{N}\sum_{b=1}^{N} q_{b,i}\cos(n\psi_b); \qquad q_{s,i} = \frac{2}{N}\sum_{b=1}^{N} q_{b,i}\sin(n\psi_b) \tag{2}$$

Equations (2) determine the rotor coordinates once that the blade coordinates are known. The inverse transformation, yielding the blade coordinate given the rotor coordinates, is represented by Equation (3):

$$q_{b,i} = q_{0,i} + q_{c,i}\cos(\psi_b) + q_{s,i}\sin(\psi_b) \tag{3}$$

In principle, MBC transformation can be used as data pre-processing before applying OMA algorithms. Acceleration of several points on the blades and the rotor azimuth angle are acquired together with accelerations of points on the tower and nacelle (non-rotating subsystems). These accelerations are collected as time histories and they can be the results of a measurement campaign on a wind turbine operating in the field or data obtained from aeroelastic codes for different values of wind speed, turbulence, etc.

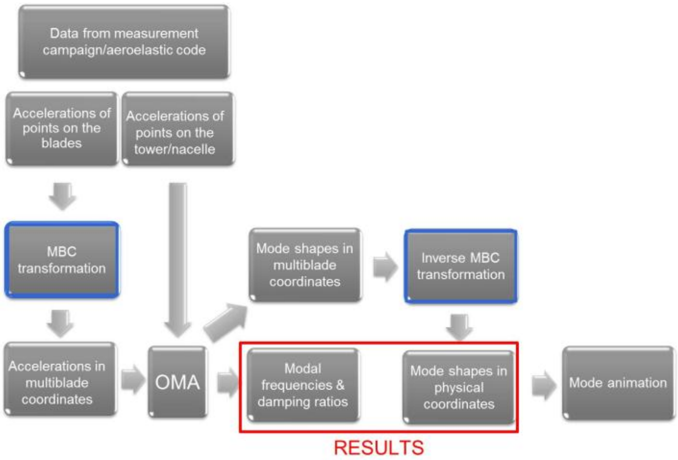

Figure 1: Multi-Blade Coordinate transformation: application scheme

MBC transformation is applied to the accelerations measured on the blades taking into account the acquired azimuth data. The accelerations in multi-blade coordinates together with the ones from the tower and the nacelle are the input for OMA algorithm that will be described in the next section. The outputs of OMA are the natural frequencies, damping ratios and mode shapes. The latest are expressed in multi-blade coordinates and they need to be transformed back to physical coordinates by means of the inverse MBC transformation. The mode shapes can finally be animated. The whole process is shown in Figure 1.

Several studies have successfully applied MBC transformation to data from aeroelastic codes [5, 6, 7]. Only few preliminary studies have been accomplished in the experimental field [8, 9].

One of the main limiting factors is due to the technical difficulties in obtaining experimental data while a wind turbine is rotating. Several challenges need to be faced: accelerometers should be mounted in the same position and orientation on the blades and data from rotor and from tower-nacelle must be synchronized. Furthermore, the readings of the accelerometers located in the same positions on different blades can be different and it can be an obstacle for the application of MBC since it requires the rotor isotropy as well as the sensors isotropy. These assumptions are never completely fulfilled. This is the reason why in the future it will be interesting to analyze in depth the application of Lyapunov-Floquet analysis approach since it does not set any isotropy limitation.

1.2 Operational Modal Analysis (OMA)

Operational Modal Analysis (OMA) technique, also known as output-only modal analysis, allows identifying modal parameters by using operational measurements such as accelerations measured on several points attached to the structure. The main reason why OMA needs to be applied is that the behavior of a structure in real operating conditions is usually different from the laboratory conditions. It can be due to several reasons such as non-linearity, real loading conditions, environmental influences, etc. There can also be practical motivations like the inability to measure input forces or the impossibility to have access to the structure or the presence of heavy ambient excitation. In the past years OMA has been widely applied in several fields: bridges, airplanes, spacecraft, wind turbines and stadiums.

OMA represents an extension of common input-output modal analysis techniques in the cases in which the input forces cannot be measured. In order to extend common identification methods to these situations, the system must comply with three main assumptions. It must be Linear Time Invariant, the excitation forces must be represented by a flat white noise spectrum in the band of interest. Finally the forces acting on the structure must be uniformly distributed and uncorrelated. The better these assumptions are fulfilled, the better the quality of the estimated modal parameters.

Several OMA techniques have been developed and evaluated in the past years. In this paper, the PolyMAX method [10] has been selected to perform the operational modal analysis. It has been developed as a polyreference version of the least-squares complex frequency-domain (LSCF) estimation method using a so-called right matrix-fraction model.

In case of Experimental Modal Analysis, the modal decomposition of an FRF matrix $[H(\omega)]$ is:

$$[\mathrm{H}(\omega)]= \sum_{i=1}^{N} \frac{\{v_i\}\langle l_i^T\rangle}{j\omega-\lambda_i} + \frac{\{v_i^*\}\langle l_i^H\rangle}{j\omega-\lambda_i^*}. \tag{4}$$

where l is the number of outputs; N is the number of modes and half of the system order, * is the complex conjugate operator, ^{H} is the complex conjugate transpose of a matrix, $\{v_i\}$ are the mode shapes, $\langle l_i^T \rangle$ are the modal participation factors and λ_i are the poles. The input spectra $[S_{uu}(\omega)]$ and output spectra $[S_{yy}(\omega)]$ of a system represented by the FRF matrix in Equation (4) are related as:

$$[S_{yy}(\omega)] = [H(\omega)][S_{uu}(\omega)][H(\omega)]^H. \tag{5}$$

In case of operational data, output spectra are the only available information. The deterministic knowledge of the input is replaced by the assumption that the input is white noise. The PolyMAX algorithm greatly facilitates the operational modal parameter estimation process by producing extremely clear stabilization diagrams, making the pole selection a lot easier by means of estimating unstable poles (i.e. mathematical or noise modes) with negative damping making them relatively easy to separate from the stable poles (i.e. system modes).

2 NREL OFFSHORE 5-MW BASELINE WIND TURBINE

The NREL offshore 5-MW baseline wind turbine has been developed by the National Renewable Energy Laboratory (NREL) to support concept studies aimed at assessing offshore wind technology. It is a conventional three-bladed upwind variable-speed variable blade-to-pitch-to-feather-controlled turbine [11]. The aeroelastic solution has been computed by using Samcef for Wind Turbines (S4WT). The model has been built as simple as possible in order to characterize the global dynamic behavior of the full-scale wind turbine. The model is shown in Figure 2 and its main parameters are listed in Table 1.

It can be divided into three main parts:

- Tower: 5 elastic beam elements with lumped masses and hinged to the ground;
- Rotor: three identical blades modeled with 17 sections with specific mass, elastic and aerodynamic properties;
- Drivetrain: one degree of freedom with gear ratio equal to 97 between the Low Speed Shaft (LSS) and the High Speed Shaft (HSS).

Figure 2: NREL 5-MW S4WT model (left); Test.Lab geometry (right)

Table 1: List of wind turbine main parameters

Blade length	61.5 m
Blade mass	17740 Kg
Tower height	87.6 m
Tower mass	347460 Kg
Gearbox ratio	97:1

The Kaimal turbulence model has been considered for performing the analysis. In Table 2 some of the main wind parameters are indicated. Figure 3 shows the main wind component in the X direction (from LSS to HSS) and the turbulent fluctuations in the other two directions. Figure 3 shows also the generator power during the simulation that lasts 800 seconds. The sampling frequency is set to 100 Hz. Long time histories are usually required for confident modal parameter estimation, even if on the other hand a small sampling frequency is needed to better determine low frequency modes. The interesting modes are at very low frequencies; so a down-sampling to 10 Hz has been performed in the first part of the analysis.

Table 2: List of wind parameters

Turbulence model	Kaimal
Wind reference speed at the reference height	17 m/s
Reference height	90 m
IEC turbulence type	Normal turbulence

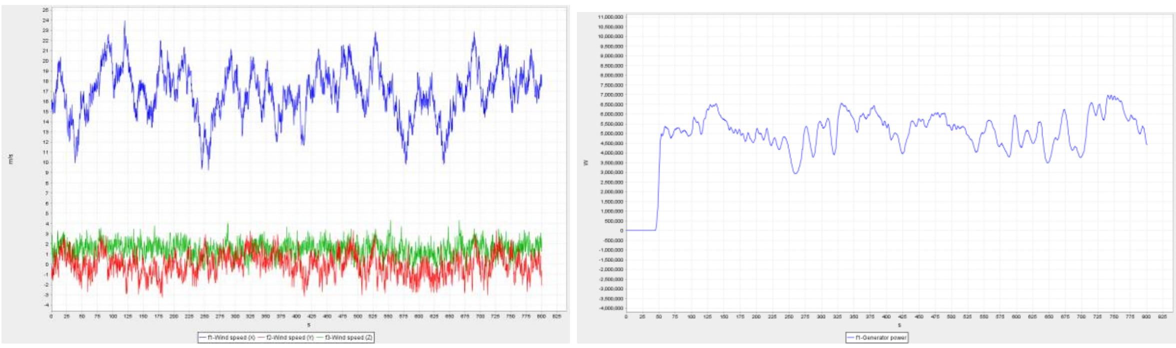

Figure 3: Wind speed in the three directions (left); Generator power curve (right)

3 MULTI-BLADE COORDINATE TRANSFORMATION APPLIED TO SIMULATED DATA

The wind turbine has been instrumented by means of several virtual accelerometers: three sensors along the tower, one at the hub center and five sensors per-blade located on the pitch axis. The signals are obtained in a local reference frame in which the X axis is the blade axis (oriented toward the blade tip), the Y axis is aligned with the chord-line and belongs to the blade section plane (oriented toward the leading edge) and the Z axis is normal to the chord line and belongs to the blade section plane.

In [12] the same wind turbine has been analyzed in parked conditions, which means when the blades are parked and the generator disconnected. In Table 3 the modal parameters in parked conditions extracted from the model (S4WT) are compared to the one obtained by applying Operational Modal Analysis to the acceleration data (OMA) and to the data obtained by using both the FAST model and the ADAMS model; in FAST the natural frequencies are calculated by performing an eigenanalysis on the first-order matrix created from a linearization analysis, while in ADAMS a command that linearizes the complete model and compute eigenvalues is used.

Table 3: Natural frequencies in parked conditions using different approaches; STS: side-to-side; FA: fore-aft; blade modes are described based on their main motion orientation

Description	**Natural frequencies [Hz]**			
	S4WT	**OMA**	**FAST**	**ADAMS**
1st Tower STS	0.31	0.31	0.31	0.32
1st Tower FA	0.32	0.33	0.32	0.32
1st Flap Yaw	0.66	0.67	0.67	0.63
1st Flap Pitch	0.66	0.68	0.67	0.67
1st Flap Sym	0.67	0.72	0.70	0.70
1st Edge Pitch	1.07	1.06	1.08	1.07
1st Edge Yaw	1.07	1.06	1.09	1.09

Once the interesting modes have been listed, the wind turbine can be analyzed in operating conditions. The procedure shown in Figure 1 has been applied to the accelerations obtained from the model. Some considerations can be done by considering the Power Spectral Density (PSD) of the time signal before and after the MBC transformation.

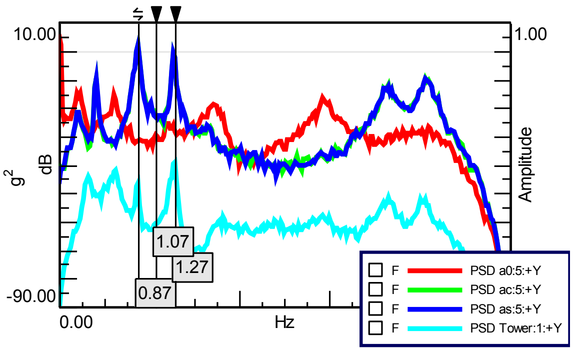

Figure 4: Power Spectral Density of accelerations measured at the tower top and at the tip of the blades in operating conditions after the application of MBC transformation

The PSDs have been calculated by using the Welch's estimator. The data have been divided up into smaller blocks to improve the resolution. To achieve a high calculation performance, the algorithm requires that the block size be a power of 2; so a value equal to 512 has been chosen with an overlapping between the blocks of 66% to compensate the effects of using Hanning windows in time domain. In Figure 4, PSDs of accelerations at the blade tip after MBC transformation are compared to the PSD obtained considering the acceleration at the tower top. The anti-symmetric coordinates (indicated as *ac* and *as*) follow each other with a very good approximation, while the symmetric component (named *a0*) has a different behavior. It can be stated that MBC transformation separates the collective blade components from the anti-symmetric ones.

It is also important to note that the peaks seen on the MBC coordinates can also be outlined in the tower top acceleration spectra as can be seen in Figure 4. It is possible to identify many of the rotor modes only using tower and nacelle data.

4 MODAL PARAMETER ESTIMATION IN OPERATING CONDITIONS

Once the MBC transformation has been applied, Operational PolyMAX can be used for estimating the modal parameters in the case in which the wind turbine is operating. Natural frequencies and damping ratios can be obtained directly, while mode shapes need to be transformed back to the physical coordinates in order to be animated.

In a preliminary study, the edgewise modes have been considered. In Table 4, the first edgewise modes in parked conditions are compared to the ones obtained by using the MBC procedure. The same analysis could be performed in the flapwise direction.

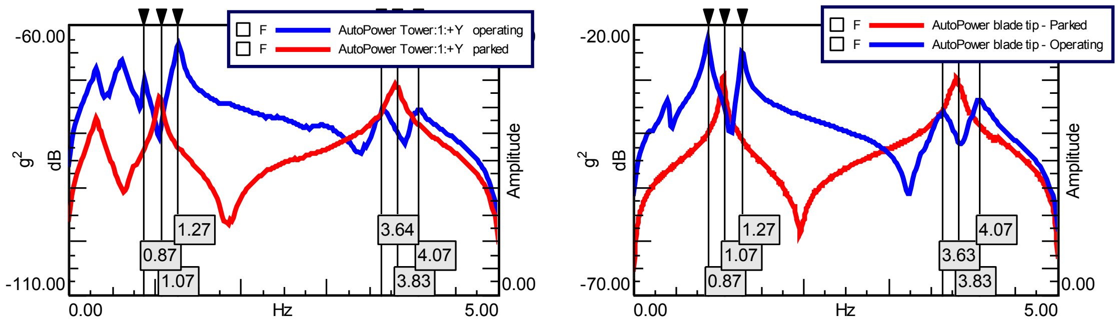

Figure 5: AutoPowers of accelerations measured at the tower top (left) and at the blade tip (right) in the edgewise direction both in operating and parked conditions

Table 4: Edgewise modes comparison: Parked conditions vs. Rotating conditions

	OMA – Parked [Hz]	MBC+OMA – Rotating [Hz]
1st Edge Pitch	1.07	0.87
1st Edge Yaw	1.07	1.27
2nd Edge Pitch	3.82	3.63
2nd Edge Yaw	3.83	4.07

As can be seen also from Figure 5, the two edgewise modes split into two modes at different frequencies, named whirling modes. In Figure 5 the auto-powers obtained from accelerations measured at the tower top and at the blade tip are shown and compared to the case in which the wind turbine is in parked conditions. MBC transformation enables observing and identifying the whirling phenomenon transforming the blade responses into a ground coordinate system. The two whirling modes are separated by 2ω in accordance with the literature, where ω is the fundamental harmonic frequency equal to 0.20 Hz because of an averaged rotational speed equal to 12 rpm. Once that the natural frequencies and the damping ratios have been evaluated, the mode shapes need to be converted back to the physical coordinates in order to be animated and compared to the ones obtained in parked conditions by using the Modal Assurance Criterion (MAC).

CONCLUSIONS

The paper presents the application of Operational Modal Analysis (OMA) to a reference operating wind turbine in a simulation environment by using an aeroelastic code. The technique can be straightforward applied only if the turbine is in parked conditions with the brake engaged. If the blades are rotating, several steps are needed in order to apply the conventional OMA technique.

First of all, the so called Multi-Blade Coordinate transformation need to be applied to convert the Linear Time Periodic system into a Linear Time Invariant one overcoming the limitation due to the time varying nature of the structure. The whirling phenomenon can be observed by comparing the spectra in parked conditions with the ones in operating conditions after the MBC transformation.

While in this work the accelerations were simulated using an aeroelastic code for wind turbine, the same techniques can be applied for structural monitoring of a real wind turbine. The application of MBC requires the rotor and sensors isotropy but these assumptions are never completely fulfilled. This is the reason why it can be interesting to analyze the application of Lyapunov-Floquet analysis approach that does not set any isotropy limitation.

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